Low power consumption lasers for next generation miniature optical spectrometers for trace gas analysis

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ABSTRACT

The air quality of any manned spacecraft needs to be continuously monitored in order to safeguard the health of the crew. Air quality monitoring grows in importance as mission duration increases. Due to the small size, low power draw, and performance reliability, semiconductor laser-based instruments are viable candidates for this purpose. Achieving a minimum instrument size requires lasers with emission wavelength coinciding with the absorption of the fundamental absorption lines of the target gases, which are mostly in the 3.0-5.0 μm wavelength range. In this paper we report on our progress developing high wall plug efficiency type-I quantum-well GaSb-based diode lasers operating at room temperatures in the spectral region near 3.0-3.5 μm and quantum cascade (QC) lasers in the 4.0-5.0 μm range. These lasers will enable the development of miniature, low-power laser spectrometers for environmental monitoring of the spacecraft.

BACKGROUND

A need exists for analyzers that can measure quality and trace contaminants in air on board spacecraft. Several types of instruments may be considered for continuous air quality monitoring within the space station.

a- Mass spectrometry (MS) is a powerful analytical technique for the determination of the elemental composition of a sample or molecule.[1] The MS principle consists of ionizing chemical compounds to generate charged molecules or molecule fragments and measurement of their mass to charge ratio. The technique has the advantage of: high sensitivity analysis (ppb to ppt); multi molecular, quasi simultaneous analysis; moderately compact and robust instrument size; and the capability of isotopic analysis. The constraints for long duration space missions include: high power consumption; high vacuum (10^{-5} Torr or better); the requirement of waste gas disposal; and frequent calibration. Mass spectrometer experience has indicated that the operating life of the MS is limited by the operating life of the ion pump, which maintains the MS vacuum.

b- Fourier transform infrared spectrometery (FTIR) is another technique widely used in laboratory, environmental, and industrial quality control applications, and is a candidate for long duration space missions.[2] This type of spectrometer is based on the Michelson interferometer using one stationary and one moving mirror. The combined beams interfere to produce time-varying beat patterns as the scanning mirror moves. The acquired waveform is an interferogram. A Fourier transformation is used to convert the interferogram into a spectrum. The drawback of an FTIR is its mechanical complexity. Such complex elements include moving optical elements which have to be guided with very high precision over an extended distance, and very high alignment stability required for all optical components in the interferometer.

c- Gas chromatography (GC) is mostly used in analytical chemistry for separating and analyzing compounds that can be vaporized without decomposition. Typical uses of GC include testing the purity of a particular substance or separating the different components of a mixture (the relative amounts of such components can also be determined). In gas chromatography, the *moving phase* (or "mobile phase") is a carrier gas, usually an inert gas such as helium or nonreactive gas such as nitrogen The requirements for preparation and extraction of gas samples results in a long response time, which is incompatible with continuous monitoring.

d- Optical absorption spectroscopy or laser-based infrared spectroscopy is an efficient method of detecting various gas species in the atmosphere through optical interaction.[3] If the number of targets is small, the laser instrument has the potential to have the lowest mass and volume footprint of monitoring technologies.[4] In order to achieve a minimal footprint instrument, it is necessary to employ a laser that emits at the fundamental absorption wavelength of the target gas which are mostly in the 3–5 µm range. The recent progress of semiconductor lasers operating in this spectral range including Interband Cascade Lasers,[5] Quantum Cascade lasers,[6] and diode lasers,[7] have increased the potential of a compact, low power laser based instrument with very high reliability that could be used in man space mission

InGaAsSb type-1 LASERS

Until recently continuous wave (CW) room temperature operation of diode lasers was restricted to wavelengths below 2.7 µm due to the complexity of the expitaxial growth of the lasing material. During the past few years major progress was made for extending the wavelength of diode lasers beyond 2.7 µm resulting from several breakthroughs in the epitaxial growth and bandgap design of GaSb-based lasers. This breakthrough result is due to a novel design of the strain-engineered quantum-well (QW) active region and quinternary barriers and due to optimization of device material composition and growth conditions (growth temperatures and rates). Our recent results shown in Figure 1. We have demonstrated emission between 3.1 and 3.2 µm from narrow ridge, single spatial mode devices operating in CW mode up to a maximum temperature of 57 ºC. Our results show a clear path to GaSb-based lasers operating up to 3.5 µm spectral range at room temperature and with low bias.

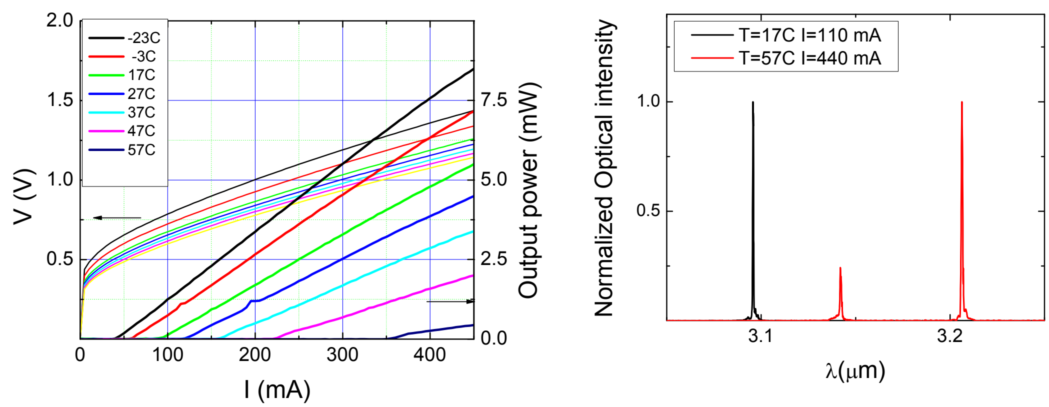

Figure 1: Continuous wave (CW) measurements of a single spatial mode laser emitting near 3.2 µm. Maximum CW operating temperature is near 60 ºC.

In tunable laser spectroscopy, single frequency operation of the laser is required which can be achieved by fabricating single spatial mode laterally coupled distributed feedback laser [8]. The entire fabrication of a laterally coupled DFB laser requires a single epitaxial growth and has been demonstrated at other wavelengths to have a much higher yield and reliability over the conventional DFB fabrication which requires as many as three epitaxial growths. In collaboration with SUNY at Stony Brook, we are developing space qualified single frequency diode lasers in the 3.0-3.5 µm range. In Figure 2, we show a scanning electron micrograph (SEM) of our current laser fabrication results. Coupled with our thick dielectric techniques that make a marked difference on waveguide loss, we will integrate distributed feedback gratings in the dielectric for single spectral mode emission.

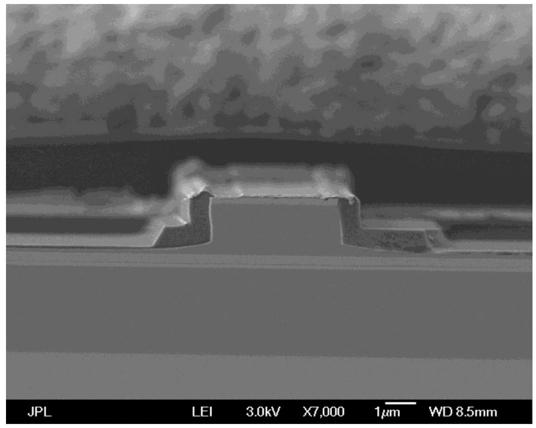

Figure 2: Fabrication of narrow ridge, single spatial mode lasers. The GaSb waveguide is dry-etched, giving highly anisotropic side walls. Thick SiN_x is used to separate the optical mode from the loss metal top contact and heat dissipation layers.

4-5 µm QUANTUM CASCADE LASERS

To be useful for space applications, semiconductor lasers in the 4.0-5.0 µm range require an order of magnitude less power than what is currently achievable. Performance from QC lasers has improved substantially over the past several years. From wall-plug efficiencies in the few percent range at best in 2004 (Ref. 6), we have now seen wall-plug efficiencies exceeding 12% in continuous operation mode at room temperature[11], and wall-plug efficiencies exceeding 50% in pulsed mode operation at low temperatures.[7,8] While these lasers are capable of emitting a substantial amount of output power, they also require a large input power—for example, >1.5 W emission for >18 W of input in Ref. 10. Thus, to operate the laser, a thermal management system capable of dissipating ~17 W of heat is required. Laser systems of this nature are impractical for most laser spectroscopy applications.

We should recognize that "high performance" to date has been interpreted to mean high output power and/or high wall-plug efficiencies. If we are willing to relax both of those requirements, we can design "high performance" lasers that operate with minimal amounts of input power.

To reduce input power, we look at the constituents of voltage and current to QC laser operation. There are a number of ways by which we can effectively reduce operating voltage V, which is simply the number of QC active–injector region periods N_p within the QC active core multiplied by the total voltage drop per period.

$$V = N_p \bullet q(E_{ph} + \Delta)$$

With q as the electron charge, the total energy drop in each QC period is simply the energy of the photon transition E_{ph} along with the defect energy Δ. In effect, Δ is "what's left over" after the electron energy falls by a photon; more specifically, Δ includes enough energy drop for phonon depopulation of the lower laser state and the prevention of thermal backfilling into the lower laser state. While the photon energy is fixed for any particular application, we have design control over both N_p and Δ. Thus, both can theoretically be decreased in order to decrease laser operating voltage.

The other element we are able to consider is operating current, or more specifically here threshold current I_{th}. The condition for laser threshold is that optical gain equal optical loss, and thus for a QC laser one derives

$$I_{th} = \frac{\alpha_m + \alpha_w}{N_p \Gamma g_c}(d \times w \times L)$$

where α_m is the mirror loss, α_w is the waveguide loss, Γ is the confinement factor of the active core, and g_c is the per-period gain coefficient. The spatial dimensions w and L are the width and length over which the device is electrically pumped while d is thickness of the active core. From our discussion about N_p, we can see that decreasing N_p will have the negative effect of increasing I_{th}. To further complicate the analysis, in minimizing I_{th} we ideally wish to minimize the area over which the laser is electrically pumped namely w and L. However, as α_m is a function of L, decreasing L decreases α_m and in turn contributes again to an increase in I_{th}. Since laser operation fundamentally implies reaching threshold, we are left with an optimization problem. One capability that is now useful to exercise, especially since the requirement of ultra-high output power has been relaxed, is the ability to increase the as-cleaved laser facet reflectivity through facet coatings. In a sense, we are now approaching the operating regime of VCSELs; that is, we want to minimize the cavity size (*w* and *L*) while using cavity mirrors that are highly reflective to hold threshold current at an operable level.

ACKNOWLEDGEMENT

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